Evolution of Optical Spectrograph Design at ESO

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The evolution of optical spectrograph design and its implementation at ESO since 1980 is sketched out from the point of view of the instrumentation with which I have been closely involved. The instruments range from the early days of EFOSC, EMMI, UVES, GIRAFFE to the present-day X-shooter and important optical design features, such as the use of focal reducers and the white light pupil principle, are highlighted.

This is an account of developments in optical instrument design at ESO from 1981, when I joined ESO, until now. I began to write this article just as I was preparing for the 4th commissioning period of X-shooter and concluded it just after my return from Paranal, one day before the deadline. Because of the lack of time, I will focus on the projects in which I have been most involved, whether wearing the hat of system engineer, project manager, or both.

EFOSC

Before my arrival at ESO I worked for five years in the development of military infrared instruments at Philips in the Netherlands. My first project at ESO was the ESO Faint Object Spectrograph and Camera (EFOSC), which saw first light in 1984. Surprisingly, instrumentation techniques and technologies at Philips and at ESO were then not that much different. The concept of EFOSC was developed under the late Daniel Enard, then head of optical instrumentation. CCDs had recently become a viable option for astronomical instruments. At first light, EFOSC was equipped with an RCA chip of about 300 x 500 pixels and a readout noise of 30 electrons! The instrument is a focal reducer: because of the small physical size of the detector, to get any useful angular field and not oversample the seeing, it was necessary to “reduce” the telescope image plane to match the size of the chip, and also to not spread the photons over any more pixels than necessary, in view of the high readout noise. This entailed speeding up the telescope F/8 beam to F/2.5 at the detector. The innovative twist was the creation of a parallel beam space between the collimator and the camera, which allows a host of optical components, like filters, grisms, and Wollaston prisms to be inserted. The instrument had just three moving functions: a slit wheel (also used for multi-object and other masks), a filter wheel and a grism wheel. Although conceptually very simple, it could be used in eight different modes: direct imaging, long slit spectroscopy, slitless spectroscopy, echelle spectroscopy, imaging polarimetry, spectropolarimetry, coronography and multiple object spectroscopy (MOS).

EFOSC used a lens camera instead of the more traditional catadioptric (mixed lens and mirror) systems used in Schmidt cameras. This choice eliminates the central obstruction present in catadioptric cameras, which can easily cause a light loss of 30–40%. For good image quality over the complete spectral range of EFOSC (350–1000 nm) we had to use the anomalous dispersion glasses that had recently been developed by Schott and which allowed a much better colour correction than the traditional crown/flint combinations. The field lens unit of the camera acted as a vacuum window and was the only part of the detector assembly that had to be customised to interface with the instrument-specific camera optics. As detectors have grown larger in size, this has proved to be a wise decision and has allowed a standard detector cryostat to be used on most instruments, without the need to develop a new cryostat for every new instrument.

The wide spectral bandwidth of EFOSC only permitted the use of single-layer anti-reflection coatings, which caused a light loss of up to 2% per surface at the extremes of the wavelength range. So, wherever possible, lenses were cemented to reduce reflection losses. This was problematic because of the big differences in the thermal expansion coefficients of the glasses used, and so we embarked on a programme to qualify flexible cements with good UV transmission. Finally, we found a suitable candidate: silicone potting cement that had been originally developed to protect printed circuit boards against the hardships of humidity and launching accelerations. It had excellent UV transmission down to 300 nm, was flexible and had good adherence and image quality even when used in thick layers.

The focal reducer concept has been extremely influential in the design of astronomical instruments. It is the basis of the design of many ESO instruments: EFOSC2, the Danish Faint Object Spectrograph and Camera (DFOSC), the FOcal Reducer/low dispersion Spectrographs (FORS1/2), the VIsible MultiObject Spectrograph (VIMOS) and the Multi Unit Spectroscopic Explorer (MUSE), as well as numerous non-ESO instruments and those planned for Extremely Large Telescopes. It is a versatile concept that can be adapted to new detector developments: compared to the first-light detector of EFOSC with 150 thousand pixels, MUSE with its 24 channels, each with a 4k x 4k chip, has 380 million pixels, an increase of a factor of more than 2500!

EMMI

The ESO 3.6-metre telescope had a suite of instruments for imaging, multi-object spectroscopy, long slit and echelle spectroscopy. These were mounted at the Cassegrain focus according to a pre-agreed exchange schedule. These frequent exchanges were detrimental to reliability. It was also not possible to change observing mode quickly when the meteorological conditions changed. In parallel with the construction of the New Technology Telescope (NTT), ESO started to consider alternative observing strategies to maximise the scientific return and minimise maintenance — remote and service observing became buzzwords. The NTT was designed to deliver exceptional image quality. But its concept allowed only two Nasmyth foci, there was no prime focus cage and no Cassegrain focus.

The telescope designers had really got their way this time (and rightly so, as the success of the NTT proved).

This is the framework within which the concept of EMMI (ESO Multi Mode Instrument) was developed in the mid-1980s, for the most part under the leadership of Sandro D'Odorico. We realised that compared to EFOSC, we could increase the peak throughput and extend the ultraviolet coverage by using two focal reducers, each optimised for the ultraviolet and visible spectral ranges, with dedicated glasses, coatings and detectors. The versatility of EFOSC already went a long way towards providing multimode capability in a single instrument. To increase the spectral resolution capability (limited to a few 1000 with grisms), two medium resolution arms were added. Each had a reflection grating turret, and could feed the focal reducers with a long slit by inserting or retracting some flat mirrors. With this addition it was possible to reach a resolution of 20 000, and by replacing the first-order grating by an echelle, it was possible to reach 70 000 in a cross-dispersed echelle format.

Bavarian engineers, when you ask them to design multifunctional machines, will curse you — usually under their breath — and tell you that you are asking for an "eierlegende Wollmilchsau" (egg-laying woolmilkpig). They will then continue to build their beautiful machines — like BMW motor cars — that are good at only one thing and not much else. Well, in 1989 the NTT acquired its version of this mythical animal — EMMI — which was a real workhorse and stayed in operation until 2008.

EMMI was the first ESO instrument that used the "Pupille Blanche" principle, a term coined in the early 1970s by André Baranne for a novel spectrograph concept, where the beam dispersed by the grating is re-collected by the collimator optics to produce an image of the grating (the white pupil — white because here all the dispersed beams overlap again), where the camera or cross-disperser is placed. The second pass through the collimator may be thought to be a waste of photons, but compared to more traditional designs, the overall efficiency is actually improved, because the camera mouth can be placed very close to the second pupil, which eliminates vignetting. The concept also allows the grating to be used with a small angle between incident and diffracted beams, which maximises the diffraction efficiency. There is also the additional design freedom to tune the diameter of the white pupil. While the primary beam size in EMMI was 120 mm, the secondary beam had a diameter of only 50 mm (with a correspondingly larger angular field), which led to light and affordable spectrograph cameras.

Figure 1. The ESO multimode instrument (EMMI) at the NTT; photo from 1991. Shown from left to right are Sandro d'Odorico, Hans Dekker, Jean-Louis Lizon and Gianni Raffi. All are still with ESO.

UVES

The study and design of UVES, the UV–Visible Echelle Spectrograph for the VLT, started around 1990. The instrument combines many of the features that had been tested and implemented successfully in the EFOSC and EMMI designs: dioptric cameras and a dual-arm design, and a white pupil arrangement with a grating cross-disperser.

UVES was to have a spectral resolution of 40 000 with a one arcsecond slit. Spectral resolution depends only on grating depth — not on collimated beam diameter — and to reach R = 40 000 we needed a grating with a path length difference of 1.6 m (i.e. the optical path difference [OPD] between the wavefronts striking the first and last groove of the ruled surface). We realised that by using very steep "R4" gratings (that for maximum efficiency are to be used at 76 degrees, the "blaze angle") we could achieve this large depth with a collimated beam size of only 20 cm, making for a compact instrument. But for various reasons (low efficiency, the introduction of anamorphosis effects and a strong change of sampling along the orders), R4 gratings were reputed to be unsuitable for use in astronomical spectrographs After some study we realised that while this was true for R4s used in traditional arrangements, which require angles of 6–8 degrees between the incident and diffracted beams, these effects become tolerable at small angles — another point in favour of the white pupil concept, which

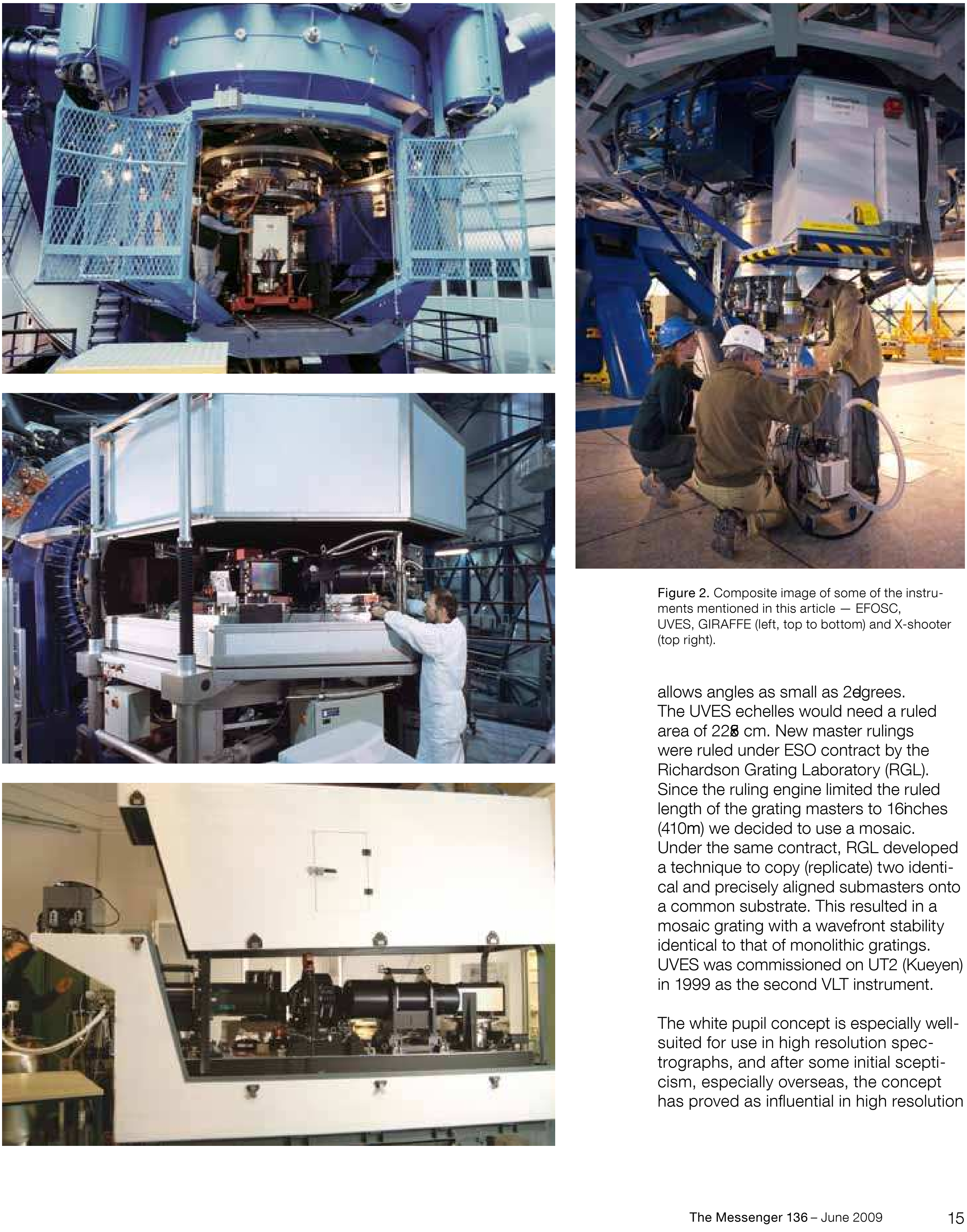

Figure 2. Composite image of some of the instruments mentioned in this article — EFOSC, UVES, GIRAFFE (left, top to bottom) and X-shooter (top right).

allows angles as small as 2 degrees. The UVES echelles would need a ruled area of 22 × 85 cm. New master rulings were ruled under ESO contract by the Richardson Grating Laboratory (RGL). Since the ruling engine limited the ruled length of the grating masters to 16 inches (410 mm) we decided to use a mosaic. Under the same contract, RGL developed a technique to copy (replicate) two identical and precisely aligned submasters onto a common substrate. This resulted in a mosaic grating with a wavefront stability identical to that of monolithic gratings. UVES was commissioned on UT2 (Kueyen) in 1999 as the second VLT instrument.

The white pupil concept is especially well-suited for use in high resolution spectrographs, and after some initial scepticism, especially overseas, the concept has proved as influential in high resolution spectrograph design as the focal reducer. (Our optical designer Bernard Delabre is good at many things, except at tooting his own horn, which is why this statement is here). The concept is used in the Fibre-fed, Extended Range, Échelle Spectrograph (FEROS) at the MPG/ESO 2.2-metre telescope, in the High Accuracy Radial Velocity Planetary Searcher (HARPS) at the ESO 3.6-metre, and for example in the High Dispersion Spectrograph (HDS) at Subaru, SARG at the Telescopio Nazionale Galileo (TNG) and the High Resolution Spectrographs for the Hobby-Ebberly Telescope (HET) and South African Large Telescope (SALT).

GIRAFFE

Unlike the previous instruments, which were all built by ESO, the GIRAFFE spectrograph of the multi-fibre FLAMES facility was designed and built by the Paris–Meudon and Geneva observatories. Final system integration and testing were done at ESO in 2001–2002, and the instrument was released in 2003. GIRAFFE is a medium-high resolution (R = 7500–30000) spectrograph for the visible range, aimed at carrying out spectroscopy of Galactic and extra-galactic objects with a high spatial density. The name is no acronym, but was inspired by the first optical design plots, where the spectro-graph was planned to be set standing vertically to minimise its footprint size on the Nasmyth A platform of UT2. During the mechanical design process it was decided to lay it horizontal on an optical table, and any resemblance to that gracious animal was lost (it now looks more like a stranded white whale, actually). GIRAFFE is fed by the robotic fibre positioner (OzPoz) developed by the Anglo-Australian Observatory, which I will not describe here.

GIRAFFE is equipped with two gratings for high and low resolution, working in orders 2–5 (low resolution) and 5–15 (high resolution). The spectral format is linear. Since the gratings work in higher orders, sorting filters are needed. The fibre slit consists of 130 fibres and is about 80 mm high. Only a lens collimator could provide the necessary field, while at the same time being fast enough to capture all the light coming from the fibres in an F/5 collecting aperture. As the attentive reader will be anticipating by now, it is a white pupil instrument, and the optical designers used that fact to create a relatively small and cheap camera.

Except for a single folding mirror, GIRAFFE is completely lens-based. This leads to a focus that is dependent on the temperature. For this reason, the fibre slit is placed on a focusing carriage, the position of which is automatically adjusted according to the temperature of the optics, in a way that is transparent to the user.

X-shooter

X-shooter is ESO’s new high efficiency, single-object, cross-dispersed echelle, point-and-shoot spectrograph with a resolution (1 arcsecond slit) of 4500 (for ultraviolet–blue and near-infrared ranges) and 7000 (visible range). It has three arms, each with its own detector, and covers, in one shot, the spectral range 0.3–2.5 μm. X-shooter is the 14th VLT instrument and replaces the first, FORS1, which has recently been mothballed. The instrument subsystems were developed and built by a consortium consisting of ten institutes in the Netherlands, Denmark, Italy and France, while ESO delivered the detector systems and was responsible for the system engineering, system integration and commissioning.

The instrument marks the current evolutionary stage of the design process that started more than 25 years ago, and combines many of the features found in the instruments previously described: dioptric cameras with apertures much smaller than the collimated beam on the grating; white pupil; efficiency optimisation by judicious splitting of the spectral range (the crossover wavelengths of the dichroics are placed at sky line features at 557 and 1020 nm). Novel optical design features in X-shooter are the use of prism cross-dispersers that are by their nature more efficient than gratings or grisms, and techniques to correct for chromaticism in the camera, that allow the number of air/glass interfaces in the cameras to be reduced to just six. As a result, X-shooter is probably one of the most efficient cross-dispersed echelle spectrographs worldwide, with a measured efficiency (top of the atmosphere to detected photo-electrons) that is larger than 30% in *B*-, *V*- and *H*-bands. Another new design feature worth mentioning is active flexure compensation: after the telescope has slewed to a new object, the instrument will align its three slits on the sky to better than 40 milliarcseconds within zenith distance 0–60 degrees, while at the same time the telescope is performing its active optics correction. X-shooter will be available in P84 on UT2 Kueyen.

Why UT2 is special

When looking back, some people tend to become sentimental. I’m sure it was just a coincidence that ESO decided to place all the VLT instruments with which I have been involved on UT2: UVES, GIRAFFE, and now X-shooter. When entering the UT2 dome, I feel a bit like I do when meeting old friends — ageing, but still going strong.

Acknowledgements

This has been a very personal account of the proverbial 1% inspiration that went into the conceptual design of some of the optical VLT instruments. The 99% perspiration aspect is not described: the toil of designing optical, mechanical, electronic and software subsystems; rejecting; redesigning; reviewing; building; testing; commissioning; and adapting them to the operational environment. Yet these aspects, to a very large extent, determine reliability, ease of maintenance and user satisfaction. I cannot begin to name all the colleagues — inside and outside ESO — who have been involved in this process. So I will not. But thank you. You know who you are.